The Antimatter Gravitation Experiment

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Abstract

This paper discusses data acquisition/analysis techniques used early on in the Antimatter Gravitation Experiment (AGE). It covers the use of lasers, photodiodes, and interferometers in conjunction with a three grating interferomer to that end. A short discussion of the first results from this experiment is included. It also explains the use of these results and how they can help in the future.

1 Introduction

1.1 Fermilab

Fermi National Accelerator Laboratory (Fermilab) is a high energy physics laboratory in Batavia, IL. It is home to Tevatron, the world's second largest particle accelerator. Measuring 4 miles in circumference, the ring-shaped Tevatron accelerates protons and antiprotons with energies approaching 1 TeV (hence the name). The protons and antiprotons collide at the Collision Detector at Fermilab and DZero, where they collect data about the collisions. Physicists there use this information to study the laws of nature.

1.2 The Antihydrogen Gravity Experiment (AGE)

For the summer of 2008, my assignment was to work on the Antihydrogen Gravity Experiment.

The purpose of this experiment is to precisely measure the earth's gravitational pull on antimatter. This is done by shooting a beam of antihydrogen through an atomic interferometer and measuring the gravitational phase shift. Since Fermilab is currently the largest antiproton source in the world, it is an ideal site for this experiment.

Earth's gravitational effect on antimatter is of interest because it has never been observed or measured. Physicists generally accept that gravity works the same on all objects of any composition, as stated by the equivalence principle. Since it has repeatedly held with matter, it is expected to also hold with antimatter. However, there are still competing theories as to what will happen. Testing the equivalence principle has the possibility to bring new understanding to General Relativity, for which it lays the foundation. Furthermore, a crucial aspect of this experiment is precision: a highly precise measurement will be sensitive to the possible existence of undiscovered forces weaker than gravity.

1.3 Summer 2008 Experimental Goals

In order to gain access to Fermilab's resources the AGE team must show that the proposed method is reasonable. So, an initial run must be done using atomic hydrogen. To this end, the most immediate short term goal was to properly align the diffraction gratings on the interferometer. The techniques used for this were based on the principles of diffraction and interferometry.

1.4 Diffraction and Interferometers

Diffraction is a theory which describes the general behavior of waves around obstacles. Interferometry is a technique that uses diffraction to take advantage of the wave properties of atoms in order to gather information about them. In this experiment, our atoms are (anti)hydrogen atoms and our obstacles are diffraction gratings.

1.4.1 Diffraction

Diffraction generally occurs when waves bend around some object. An informative example of this is the Double Slit Experiment. Designed by Thomas Young in 1861 to show the wave nature of light, its principle applies to all quantum particles.

When a wave is shot through the series of slits its amplitude undergoes superposition and interference. We can determine any shift in phase or amplitude by the diffraction pattern produced.

In Figure 1, light is first beamed through S1, then beamed through two more slits on S2. The light that passes through the two slits interferes. Let's call the distances from the center that two particular rays of light, one from slit b and the other from slit c, hit $r1$ and $r2$. If the difference between these two measurements is $m\lambda$, where m is the order and λ is the wavelength we see constructive interference and we see a "bright" spot. If it is $(m + \frac{1}{2})\lambda$, we see a "dark" spot. Anything in between is gray.

This principle extends to atoms. The de Broglie hypothesis, named after its creator, describes the wave-like nature of matter. A particle's momentum p, it reads, is inversely related to its (de Broglie) wavelength λ. Or, $p\lambda = h$,

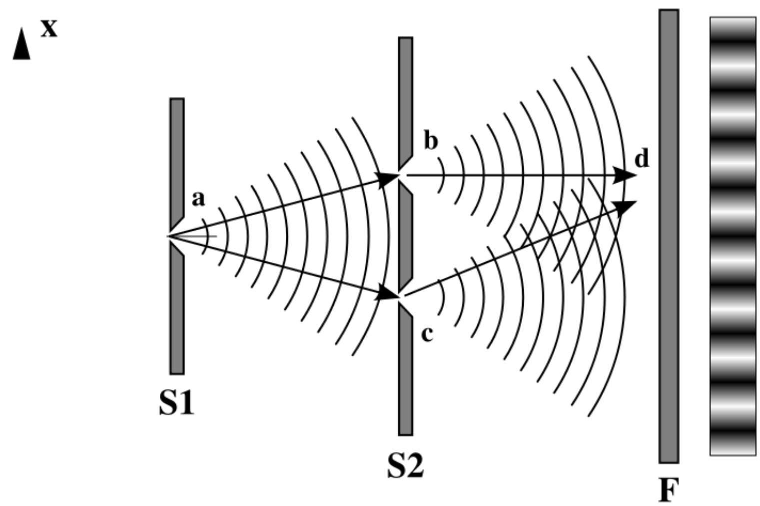

Figure 1: An example of diffraction.

where h is Planck's Constant. We take advantage of this wave-particle duality by using a technique called interferometry.

1.4.2 Interferometry

Atomic interferometry concerns itself with manipulating the wave properties of atoms. In the AGE, this is done with a series of three gratings. The first two gratings work together to create a diffraction pattern, which is beamed onto a third grating. This third grating acts as a sort of "mask" with which we use to analyze the pattern.

When we say the third grating acts as a "mask", we mean we can measure the transmission as function of the grating's position. And since we can find the phase from the grating's position, we are in effect measuring the transmission as a function of the phase.

Success is highly dependent on how precisely the gratings are aligned. Misalignment obscures the diffraction pattern, making it less useful. The goal of this summer, then, is to be able to take appropriate data from such a system and manipulate it in meaningful ways.

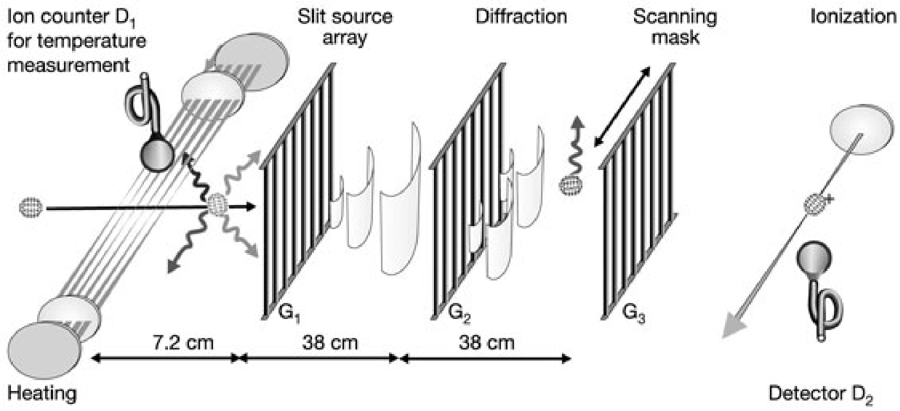

Figure 2: A three grating interferometer.

2 Data Acquisition and Analysis

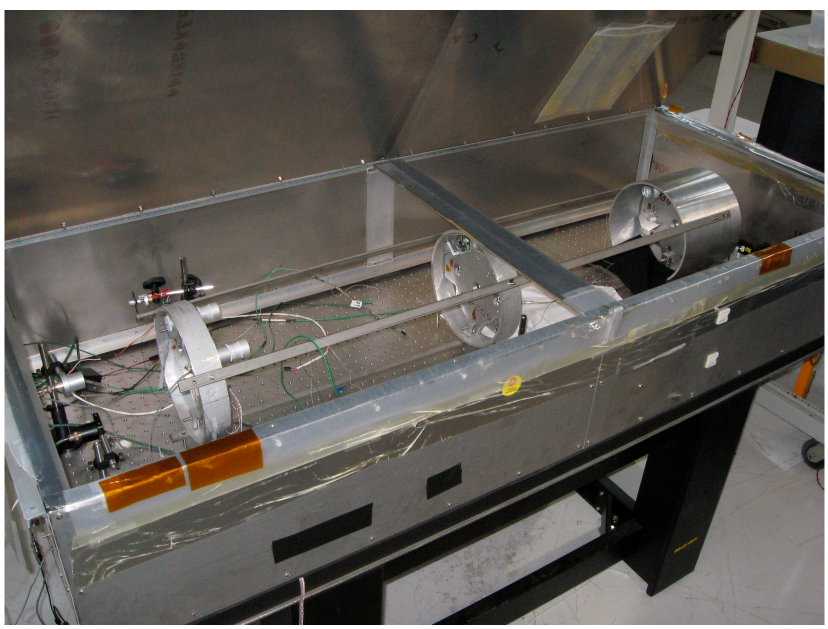

Figure 3: The interferometer we used.

In taking data, we used Rasnik analysis, alongside the LabVIEW software, to work with our photodiodes, accelerometer, and interferometer. This section will explain how they work and why we use them.

2.1 The Interferometer: An Overview of the Set Up

Our interferometer has a series of three sets of gratings and lenses, each on a disk. The distance between the first and second disks is the same as the distance between the second and third. On the first disk and third disk are two light diffraction gratings, both of which are parallel to its corresponding disk on the other plate. The middle disk is set up as to capture different orders of the diffracted beams from the first plate. The second disk has four gratings. A picture has been provided in this section.

2.2 The Photodiode

Photodiodes are devices which react to light and output a voltage reflecting its intensity. When a section of the photodiode is hit by photons, it excites electrons in the set up. This produces a voltage which is read by LabVIEW.

Figure 4: A picture of a photodiode.

The reason for using photodiodes is that it is useful to test the set up using an easily attainable source like light. This makes it much easier to test and debug things such as alignment and LabVIEW data acquisition programs. The photodiodes are connected to a terminal block that passes voltages through an ADC (Analog to Digital Converter.) This will be explained later in this section.

2.3 The Accelerometer

The accelerometer gives an output voltage which correlates with acceleration. Since the AGE requires very high precision, the accelerometer is useful for vibration studies. Even miniscule floor vibrations can shift the plates in such a way to interfere with the experiment. Therefore, it is necessary to account for these vibrations.

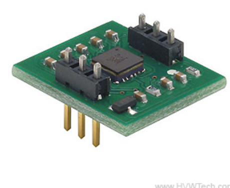

Figure 5: A picture of an accelerometer.

Like the photodiodes, the accelerometer is connected to a terminal block, which is what feeds the voltages to the computer. This will be explained later in this section.

2.4 Rasnik Analysis

Rasnik Analysis is a system that we use for positioning. When used with the photodiodes, it can return an exact position of the beam. If then, the system is even slightly off center, we can know by how much. 6

2.4.1 How It Works

The system consists of a mask, an image sensor, and a lens. The lens focuses the mask onto the image sensor. The mask produces a pattern akin to a checkerboard. Using a rasnik analysis, we can get the position of the center that it is focused on. A picture of the mask is what we're interested in.

A rasnik image, such as the one in Figure 5, contains a binary code for its position. The image shown is only a small portion of what is captured by the lens. Its irregularities are what contain the useful information. A pure checkerboard would reveal nothing. To find this information, the computer program scans the rows for two identically colored squares. This signifies the beginning of a code block, which can be either vertical or horizontal. The

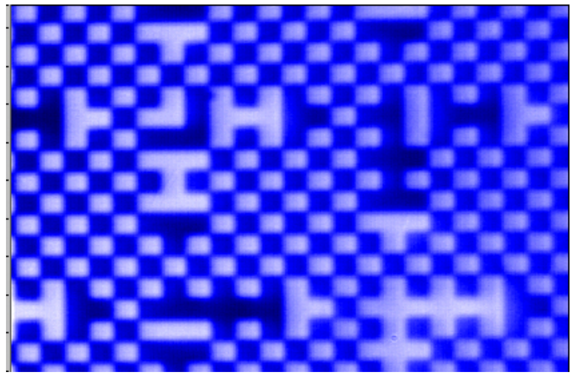

Figure 6: An example of a pattern produced by the mask.

code, like the color scheme, is binary. Its characterized by the alternating tiles. The converted numbers are what tell its position. In this way, the rasnik system is sensitive to any movement of the workspace.

The analysis of the program is performed by a combination of computer programs working together. The core program, the one that performs the analysis on the masked image, is a prewritten FORTRAN program. The program, however, needs a "driver." This "driver" connects to the camera of the rasnik instrument and saves each frame as an image, then passes it as input to the rasnik analysis program. This is done by a program we eventually built in LabVIEW.

2.5 Interfacing with LabVIEW

2.5.1 An Electrical Connector

The interferometer and other apparatus interface with LabVIEW via a National Instruments terminal block. To make use of this, we clamp wires in

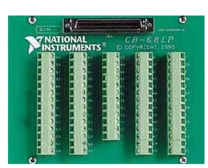

Figure 7: A terminal block.

the proper holes and screw them in. This creates an electrical connection between the apparatus and the terminal block. Analog data from the terminal block is converted to digital data via an ADC, and these are the voltage values passed to the computer. These are then caught by a data acquisition program, such as LabVIEW.

2.5.2 main.vi: The Driving DATAQ Program

The central program we wrote for data acquisition and analysis performed several functions. It stored and plotted appropriate data, provided Fast Fourier Transforms, plotted running averages, and a current view of the masked Rasnik image. The Fast Fourier Transforms (FFT) and running averages were especially useful for vibration analysis. FFTs provided us with knowledge of which frequencies were causing the most disturbance, and clued us in to their origin. Running averages helped rid the data of noise.

3 Results and Analysis

3.1 Vibration Studies

We tested our setup by generating a given sound frequency, in order to test our devices, and observing the plots given by our LabVIEW program. This way, we can also identify external frequencies. From this, we can either identify their sources or compensate for them later. To get better readings, we also used a current amplifier.

3.1.1 Fourier Analysis

When plotting the vertical acceleration and light intensity of our system over an extended period of time, it makes sense that the resulting function is sinusoidal. We can then describe it as a mathematical series of simpler oscillatory functions, "basis functions." From there, we can determine their frequencies. These type of operations fall under Fourier Analysis, named after its discoverer Joseph Fourier.

This is useful for examining the output of our diodes and our accelerometer. The voltage readings from our diodes are an indirect measure of vibration. Maximum readings occur, then, whenever the laser beams directly overlap on the diode's lens. These readings are thus sensitive to natural floor vibrations (in this case, those caused by our sound generator) which cause shifting in the plates of the interferometer, which ultimately cause shifting in the voltage readings they produce. The accelerometer directly measures vibration along the vertical axis.

Using LabVIEW, we can create Fast Fourier Transforms of the resulting functions. What this does is plot frequency against voltage (amplitude). This is how we can determine the most common frequencies experienced by the system.

3.1.2 Data

Here are our results, organized by the frequency of the sound we generated.

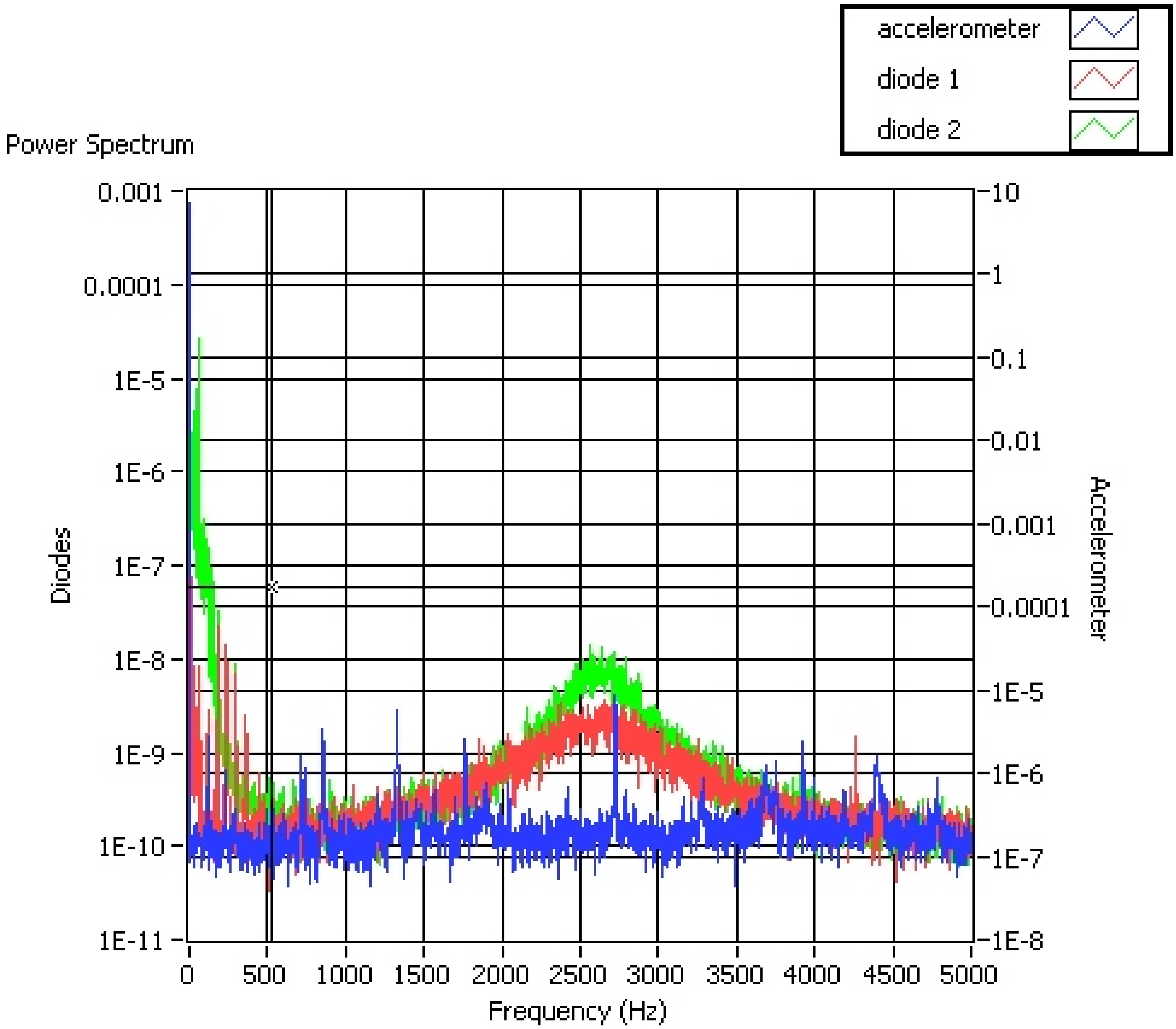

Figure 8: Our Baseline Data. We generated no sound. The peak at 2500 Hz is caused by amplifier.

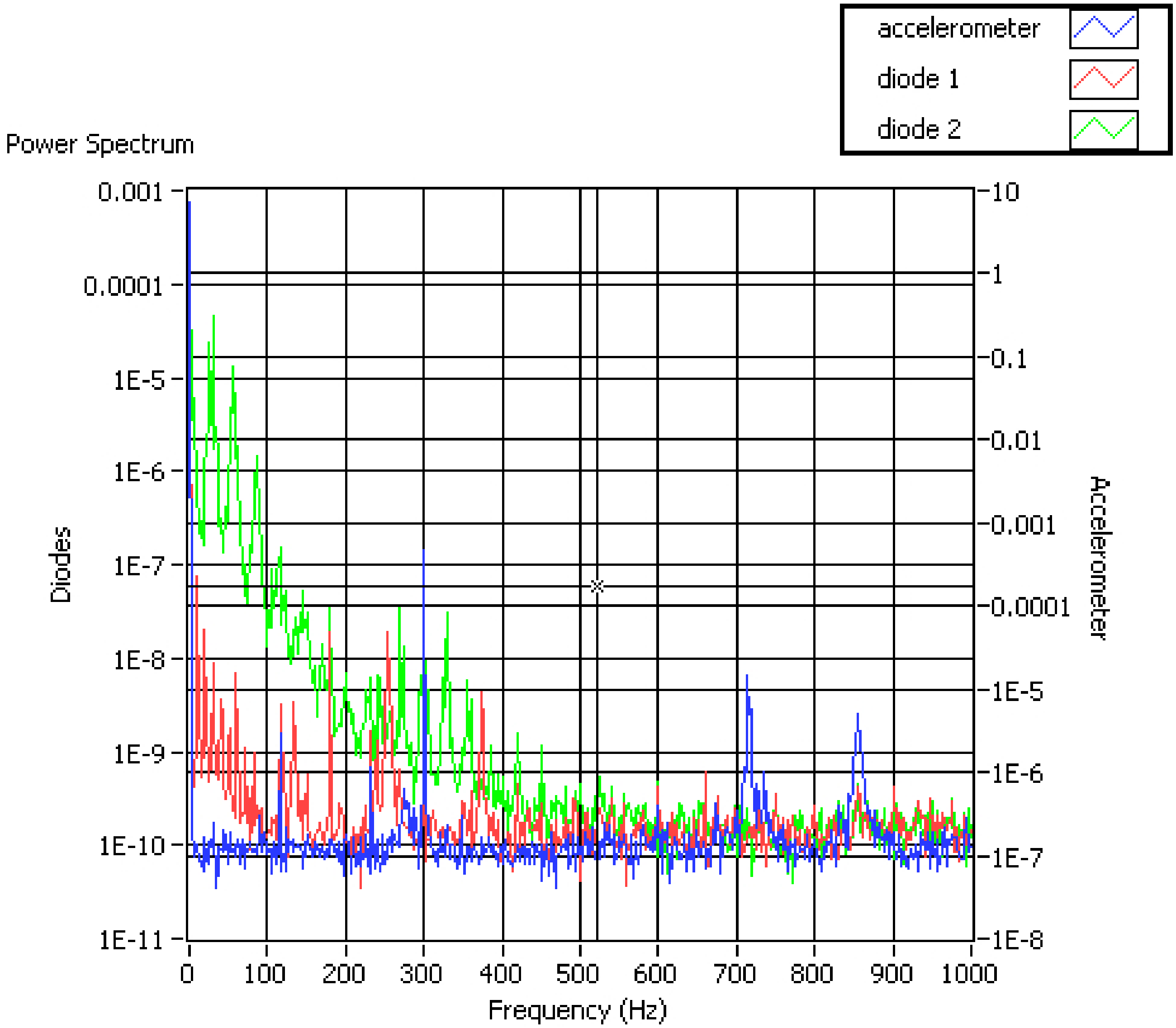

Figure 9: Results from generating 100Hz.

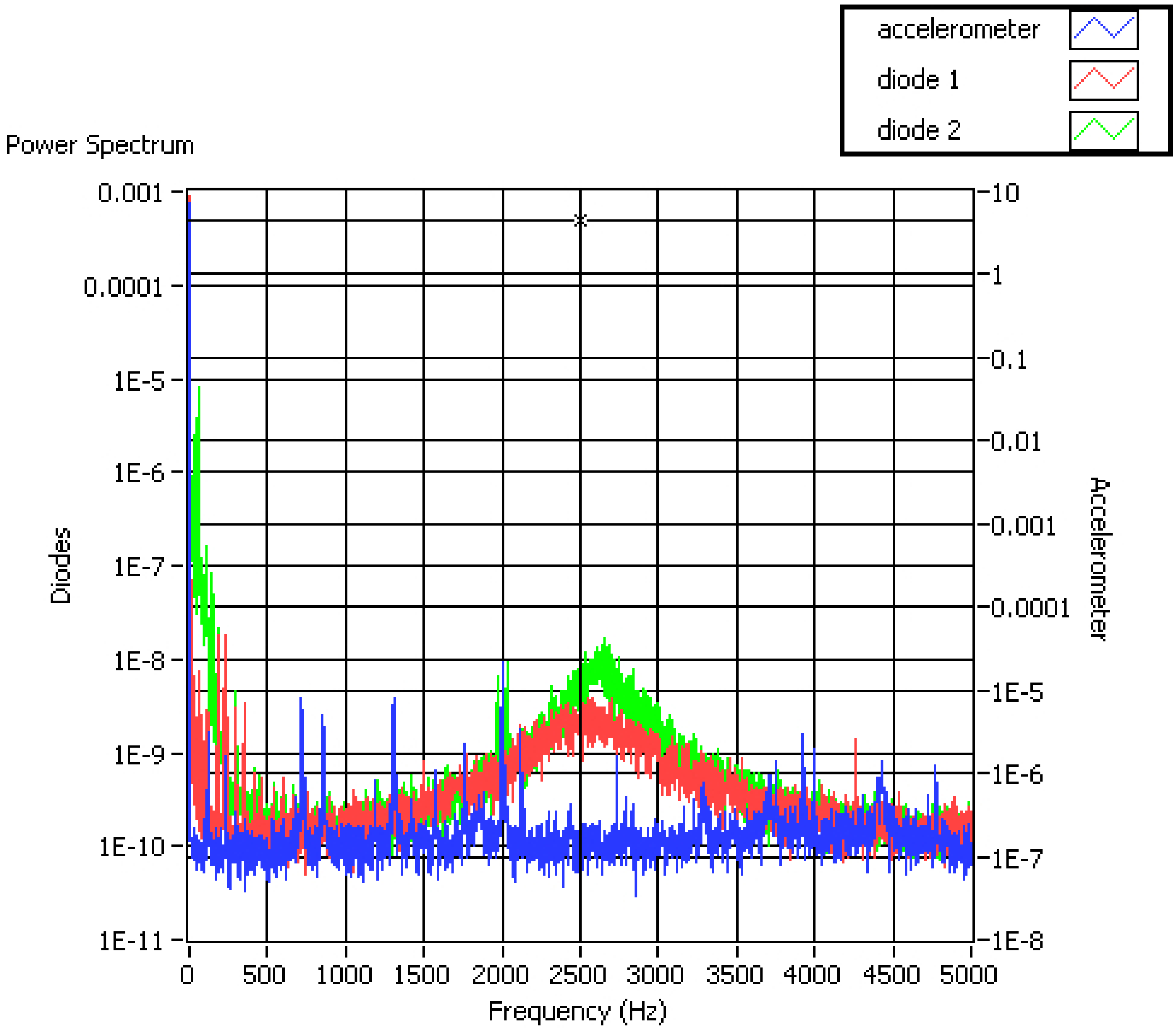

Figure 10: Results from generating 2000Hz.

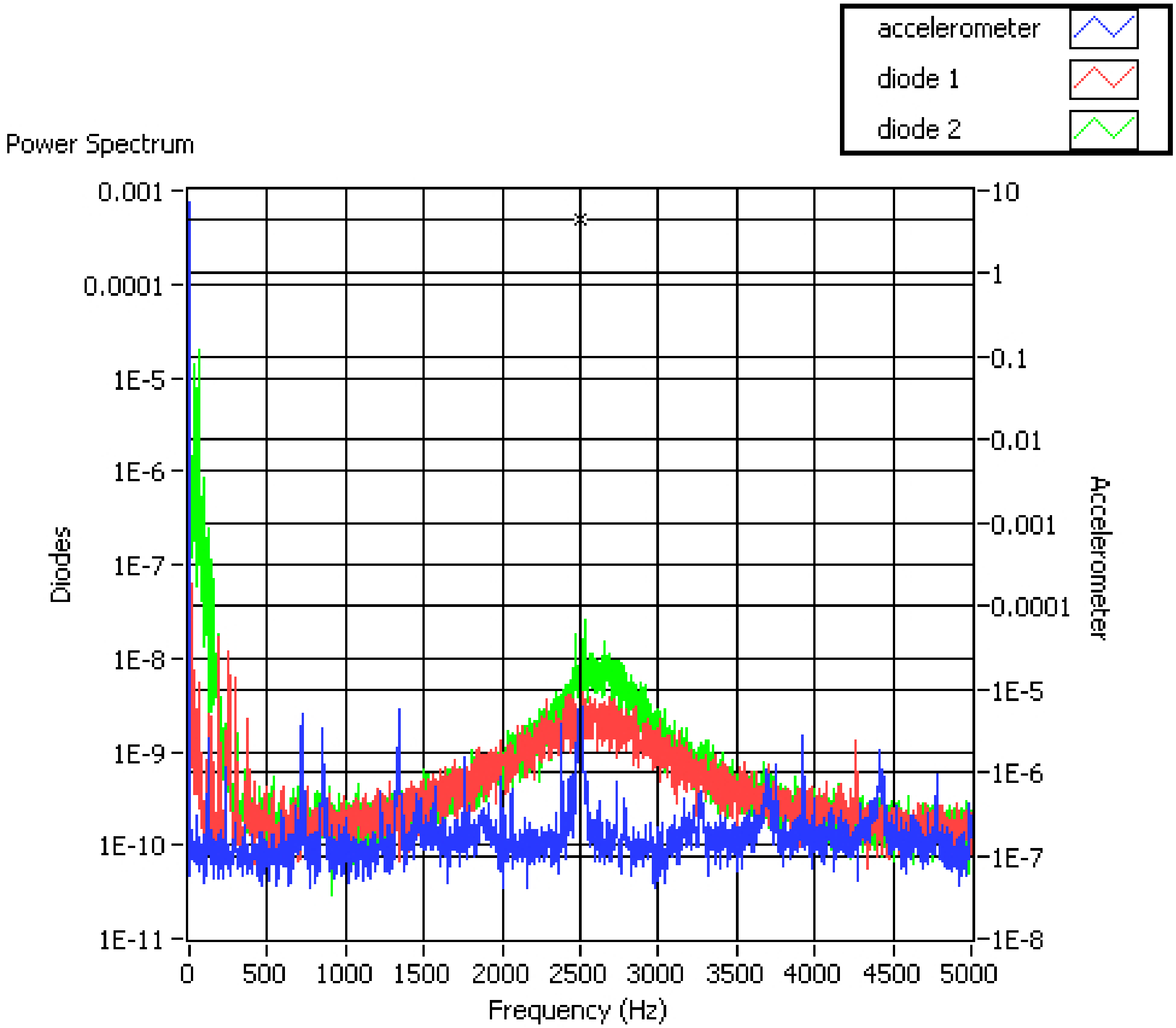

Figure 11: Results from generating 2500Hz.

3.1.3 Discussion

First, it's important to note that any readings from the diode labeled "Diode 1" should be ignored. The gratings through which that laser beam passes were not aligned properly at the time. Also, as can be seen on a large enough horizontal scale, the amplifier used for the diodes has a broad peak at 2500 Hz. One should also keep in mind that the sound generator used was a computer speaker that does not perform well at relatively low frequencies.

If we look at our base measurement, we can see a lot of background noise. Later, in Figure 2 where 100 Hz is generated, none of our instruments seem to respond. That is because this is a relatively low frequency, and our speaker is limited. However, we do see much noise in the accelerometer between 0 and 400 Hz. These are various external vibrations coming from the floor and its surroundings. For example, when we stomped on the ground or shook the setup, it was very noticeable on the graph.

In figures 9 and 10, we do see spikes in the appropriate places.

4 Conclusion

This summer we were able to put together a type of toolkit for making sense of the readings we got from our interferometry system. With regard to beam alignment, we can use lasers as a model for the future, where we will use hydrogen and antihydrogen instead. Our ability to measure vibration effects opens a few possibilities as to how we can account for them.

5 Acknowledgments

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6 Bibliography

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